

Calibration and Application of Transient Liquid Crystals for Heat Transfer Measurements

Undergraduate Honors Thesis

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by

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Abstract

Gas turbine engines are often subjected to high temperatures required to maximize efficiency. However, these temperatures exceed the melting temperature of the metal and hence turbine blades require effective cooling. Heat transfer experiments are conducted at the OSU Gas Turbine Laboratory to better understand the effects of these cooling flows. The current method of temperature measurement involves using discrete instrumentation such as resistance temperature devices (RTDs), which are limited to extracting measurements only at specific locations. Thermochromic Liquid Crystals (TLCs) provide full coverage temperature measurements that can act as boundary conditions for a conduction model to enable calculation of surface heat transfer. The crystals respond to temperature changes by reflecting light of a particular wavelength, and this apparent color change may be captured using a calibrated digital camera. There are various data available on TLCs, but industry remains cautious about the reliability of the data and requires careful verification of any measurements acquired using this technique. This thesis describes the development of a facility needed to obtain the accurate data that can demonstrate that the TLC methodology employed at OSU provides reliable temperature measurements. To conduct this experiment, a model for the steady-state calibration of the liquid crystals applied to a flat copper plate has been designed and constructed. The hue values of the reflected color are captured by a high-resolution camera and are then compared against known temperatures given by RTDs. Calibration curves for two trials are obtained, which show consistent results. The relationship between color and temperature can be well defined using a seventh degree polynomial fit.

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I am very lucky to have great parents who understand my strengths and always direct me towards the right path. I definitely would not have achieved this without their blessings. I am very grateful to all my friends who have been with me through thick and thin. Their constant motivation will always keep me going.

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Chapter 1: Introduction

1.1 Turbine Blade Cooling Experiments

The operating temperatures of Gas Turbines have increased since the 1940s in order to improve power output and efficiency [1]. These temperatures are often so high that they exceed the maximum allowable temperature of the metal blades by several hundred degrees Kelvin. In order to avoid material failure, the turbine blades are cooled by passing cooling air through internal passages inside the blade as shown in Fig. 1. The ribs in the path of the cooling air help to turbulate the airflow, which improves the heat transfer out of the blades. A serpentine model was designed to imitate the cooling process in a turbine blade for performance optimization [1]. The top cross section of the model is illustrated in fig. 2; it carries the same features as a blade's internal cooling passage including a serpentine passage and turbulator ribs.

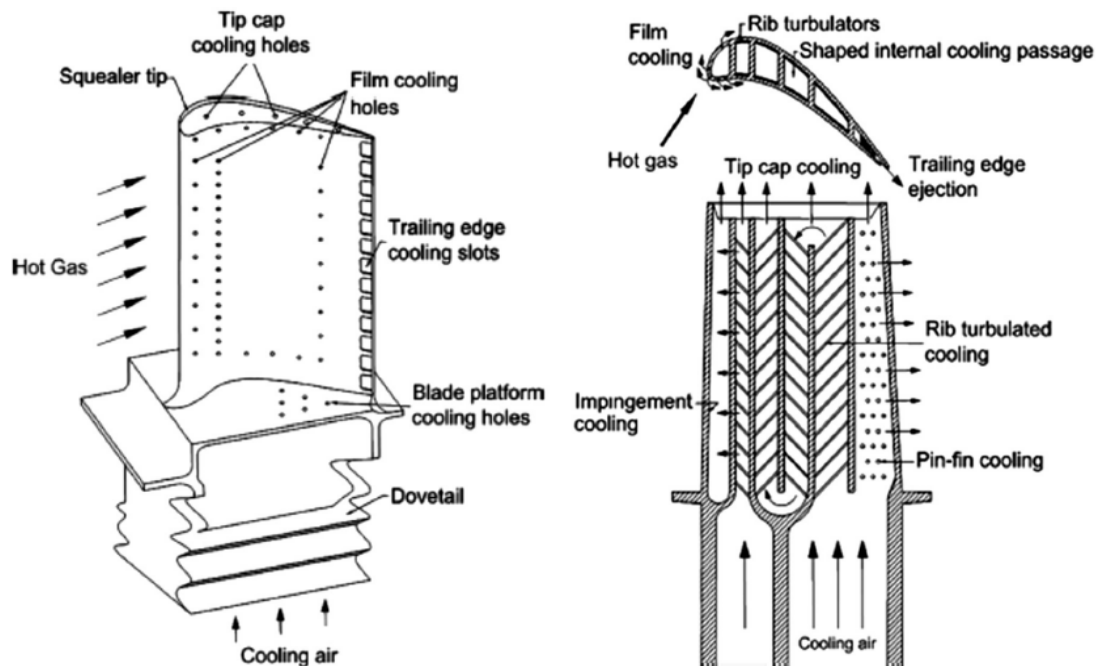


Figure 1: Cooling of typical gas turbine airfoil [1]

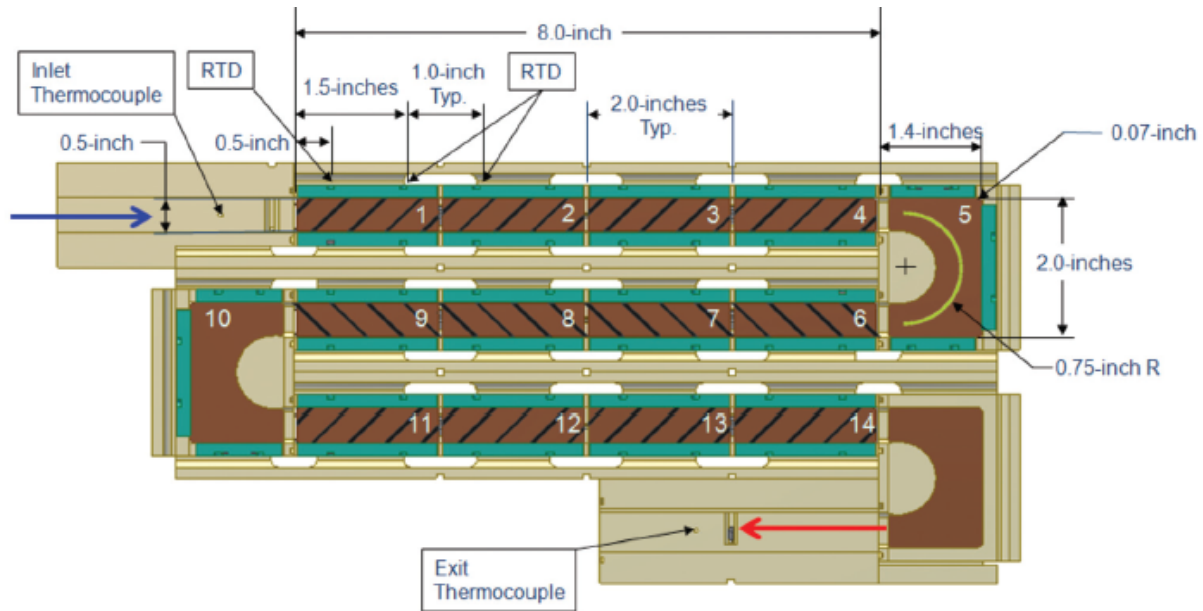


Figure 2: Schematic of Serpentine Model [1]

The model consists of a series of high conductivity copper plates that are maintained at a constant temperature using a heater. One or two RTDs were placed inside each plate. Using a computer control system, temperature was regulated based on the RTD temperature measurements. The amount of energy consumed by the heater was related to the local heat transfer rate [2]. While this technique has been trusted for many years, the RTDs and heaters only provide an average value of temperature and heat flux for each copper plate, so the spatial resolution of the data was low for heat transfer analysis. Therefore, a full coverage temperature measurement technique would be a favorable solution.

1.2 Introduction to Thermochromic Liquid Crystals (TLCs)

TLCs are organic chemicals, which develop unique temperature driven color distributions due to the thin film effect [3]. Incident light is selectively polarized according to particular wavelengths. Rotation of the polarized plane by TLCs contributes to increased reflectivity and

narrow bandwidth, ensuring purity in the reflected color. The reflected color spectrum is recorded in the RGB model and may be converted to the HSL model for convenience. A black background coating on the surface ensures clear spectral colors by totally absorbing the translucent fraction. A characteristic of the TLCs is that its color changes are both repeatable and reversible as long as they are in good condition [3]. The crystals demonstrate red and blue intervals that represent the low temperature and high temperature margins respectively [3]. There is also a gradual color gradient between the extremes, which is useful for interpolating the intermediate temperature values.

The “physical representation and visual impression of light” can be used to distinguish colors [2]. Image sensors typically detect three primary colors: red, green, and blue (RGB) [2], but color can also be represented using hue, saturation, and lightness (HSL) values [3]. Hue has been shown to largely capture the color change due to temperature in a single value. It is therefore necessary to convert the RGB signals HSL color space using the following transformations [2]:

$$H = 256 \arctan [(\sqrt{3} (G - B)) / (2R - G - B)] \quad (i)$$

$$S = 255 [1 - 3\min(R,G,B)] / (R+G+B) \quad (ii)$$

$$L = 0.299R+0.587G+0.114B \quad (iii)$$

The Hue value is the measure of the chromacity of color [2]. Saturation describes the amount of white content in the color [2]; it represents the purity of color [3]. Meanwhile, Lightness signifies the intensity of the light [2]. The applied light source also influences the color signals picked up by the camera. Illuminants with warm white temperatures (~ 3000 K) and high color rendering index are preferred to counterbalance these effects [2].

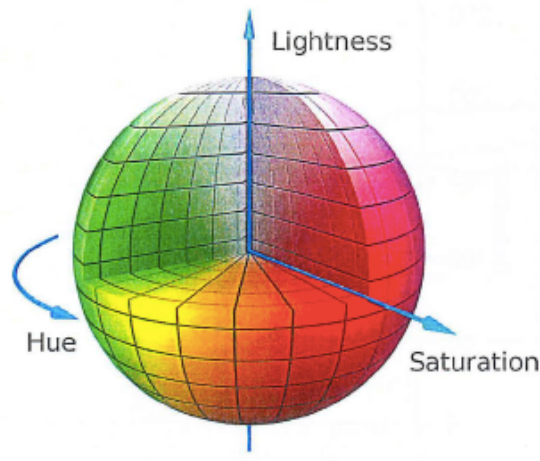


Figure 3: Visualization of HSL model [2]

1.3 Research Significance

Liquid Crystal technology has emerged as an effective full-coverage temperature measurement method. It has proven to be useful for both steady state as well as transient heat transfer experiments, due its ability to quickly respond to temperature changes. Furthermore, it can be used on complex geometries where conventional temperature measurements are difficult to implement. There are various data available on TLCs, but industry remains cautious about the reliability of the data and requires careful verification of any measurements acquired using this technique. The calibration of liquid crystals is an in-situ method and requires environment-specific calibration that depends on various factors such as background lighting, camera settings, quality and batch of liquid crystals. The purpose of my research is to obtain the accurate data needed to demonstrate that the TLC methodology employed at OSU provides reliable temperature measurements.

1.4 Overview of Thesis

This thesis has four chapters. Chapter two discusses the design of the calibration unit. This includes design of the copper plate and modifications of a vacuum desiccator that satisfies the design criteria for the calibration of TLCs. This chapter also discusses the experimental setup, procedure, and data measurement analysis. Chapter three discusses the results of the experiment. It includes various illustrations of the calibration curves of two trials and both are compared. Chapter four discusses summary and conclusions of the experiment and highlights potential future work for the research.

Chapter 2: Methodology

2.1 Design of Calibration Unit

The design of the calibration unit was inspired from *Poser* and *VonWolfersdorf's* stationary calibration setup [1]. The following were the essential criteria for design: (1) A copper plate with TLCs coated on one surface (2) A temperature gradient across the plate (3) Active temperature measurement devices (4) A vacuum chamber enclosing the setup with a clear view of TLCs to ensure steady state measurements. This section explains the design process in the creation of a calibration unit for my research.

The initial design is illustrated in Fig 4. The flat surface serves as the calibration area upon which TLCs are coated and the two handles protrude out of the vacuum chamber. Hot and cold temperatures can be applied to the handles to create a temperature differential on the plate. These handles furthermore act as supports to the plate and sit on the vacuum chamber. The chamber is tightly secured using O-rings between the clear lid and bottom of the chamber.

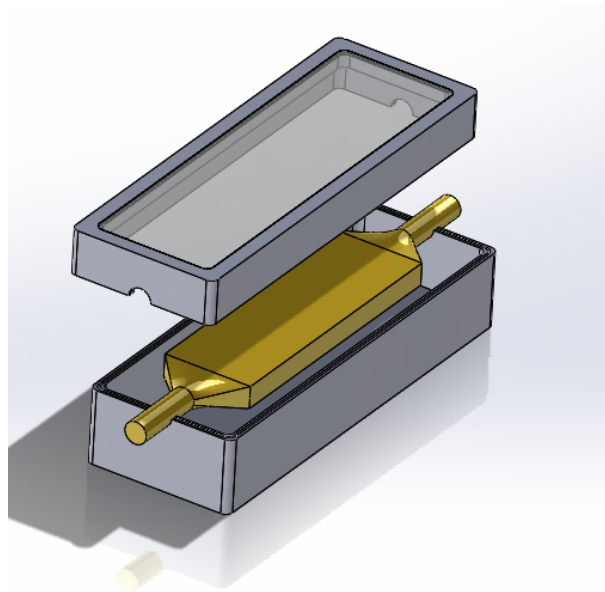


Figure 4: Calibration Unit Design I

This design has many disadvantages. Firstly, The copper plate and Vacuum chamber are hard to manufacture and the design is not very airtight. Secondly, the method of creating a temperature gradient across the plate is still unclear at this point. Thirdly, a Finite Element Analysis using ABAQUS shows that a 2-D assumption does not hold for this design. The results can be found in Appendix B.

The design of the copper plate was modified into a simpler one and changes have been made to the vacuum chamber to check any air leaks. The second design is illustrated in Fig. 5.

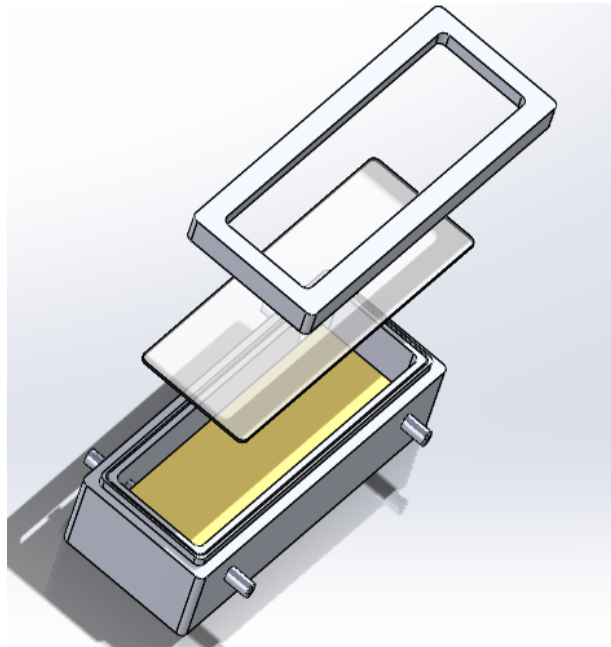


Figure 5: Calibration Unit Design II

The copper plate was modified into a simple rectangular shape with through-holes on its ends. A detailed view of the copper plate is shown in Fig. 6. A temperature gradient could be created using water chillers to pump hot and cold fluids through the copper plate using compression fittings. Several holes can be created to fix RTDs for temperature measurement. The lid with the

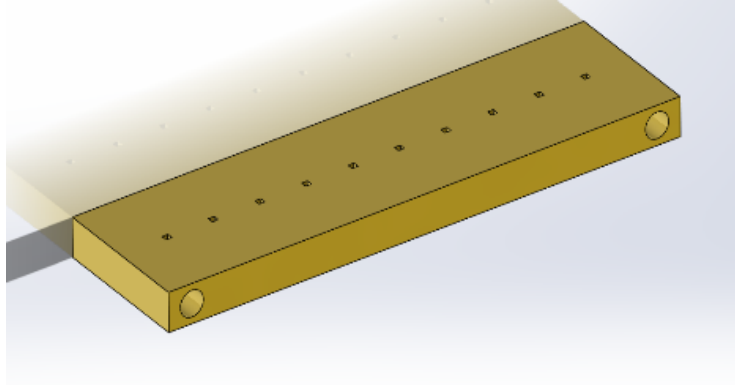
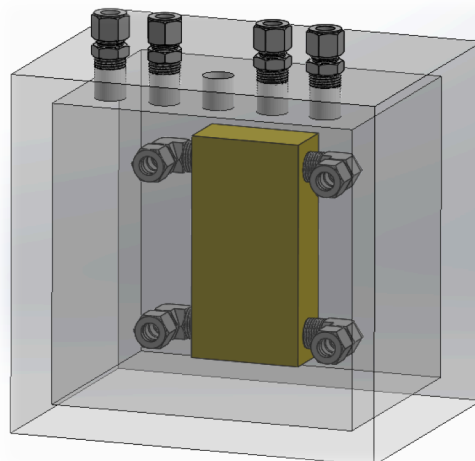


Figure 6: Copper Plate Design II

Perspex glass would sit on top of the chamber and can be tightly secured using a lid to ensure an airtight design. Results from Finite Element Analysis shown in Appendix B conclude that the second design is more favorable to a linear temperature gradient and the 2-D heat transfer assumption holds. An alternative to manufacturing the aluminum vacuum chamber can eliminate high manufacturing costs. An acrylic vacuum chamber by “best value vacs” as shown in Fig. 7(a) is available in the market for a reasonable price and delivery time. The product comes with built in vacuum valves and a pressure meter.



(a)



(b)

Figure 7: (a) Acrylic Vacuum Chamber. (b) CAD model of modified vacuum chamber

The colorless, clear acrylic is favorable for viewing TLCs on the copper plate. Fig. 7(b) shows the CAD model of the modified vacuum chamber. Five ½” NPT holes are drilled onto the lid to fix compression fittings from Swagelok. These fittings help to maintain the vacuum inside the chamber. Three RTDs are fixed at equal distances on the backside of the plate. The wires from the RTDs are sent out of the chamber through an airtight cable gland. Hot and cold fluids are circulated using fluid chillers manufactured by Haake and Lytron, respectively.

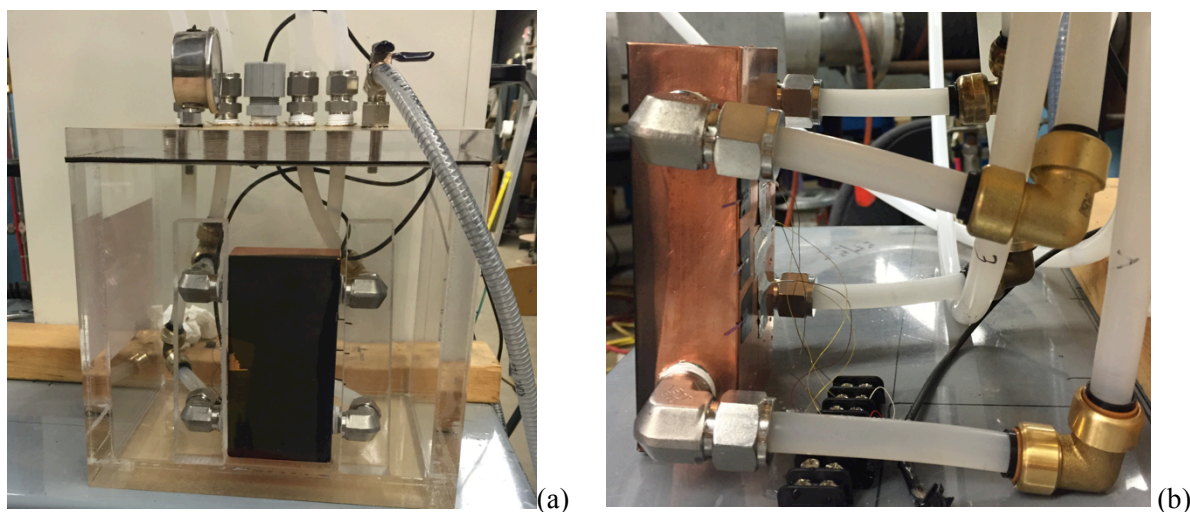


Figure 8: Picture of final calibration unit. (a) Front view (b) Side view

2.2 Procedure

The calibration unit is setup as shown in Fig.8. Hot and cold fluids are circulated through the top and bottom of the plate, respectively, and the vacuum pump is turned on. An observation trial is conducted using fluid temperatures of 40°C and 22°C, with a negative vacuum pressure of 285 mm Hg. As the temperature differential is created on the plate, the liquid crystals are seen changing color and settle down in steady state. Constant RTD readings confirm the same. Fig. 9(a) shows the observed color pattern on the coated copper plate. At this point, the temperature distribution is yet not spread out across the length of the plate.

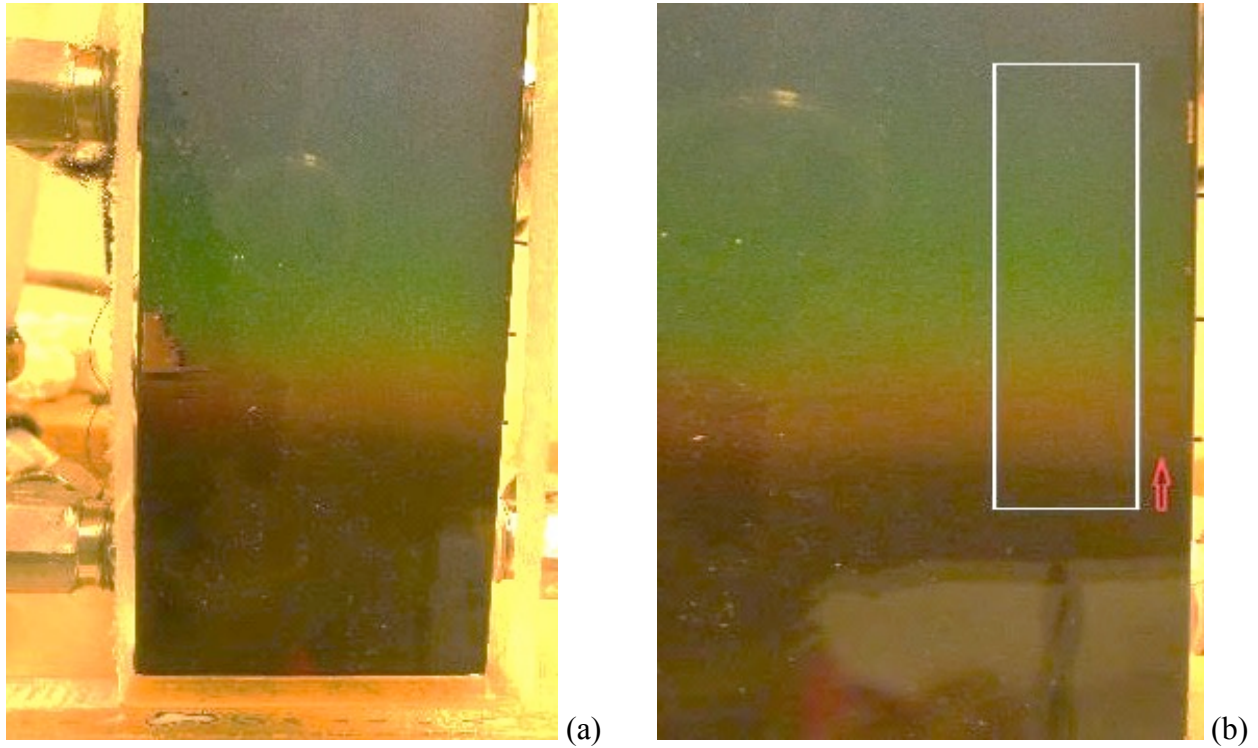


Figure 9: Pictures taken from a Panasonic Digital Camera (a) Observed color change of TLCs (b) Selected data points for interpretation

A set of sample data was selected from the picture shown in Fig. 9(b) and fed into the MATLAB code shown in Appendix A to plot RGB and Hue across the length of the plate from bottom to top, as indicated by the red arrow in Fig 9(b). The RGB values were averaged across the width of the plate. These RGB values $\in [0, 255]$ were transformed into Hue values $\in [0, 1]$ using the equations shown in chapter one. The functioning of the MATLAB code was confirmed by observing the result window. The red showed a peak at the start and conversely the blue showed a peak at the end of the graph, clearly indicating the transition from red to blue. The MATLAB code was unable to determine the Hue value for the area in black, since many different value of Hue can be used to represent black. Furthermore, the viewing angle needed adjustment to avoid reflections of the camera eye on the captured image.

The fluid temperatures were altered so that the temperature differential extended across the entire plate. Two trials were conducted after all the necessary modifications were made. The first trial had a temperature differential between 24.4°C and 38°C . The second ranged from 25.5°C to 38°C . Both trials were under a negative vacuum pressure of 381 mm Hg. Fig. 10 shows the observed color pattern for the two trials.

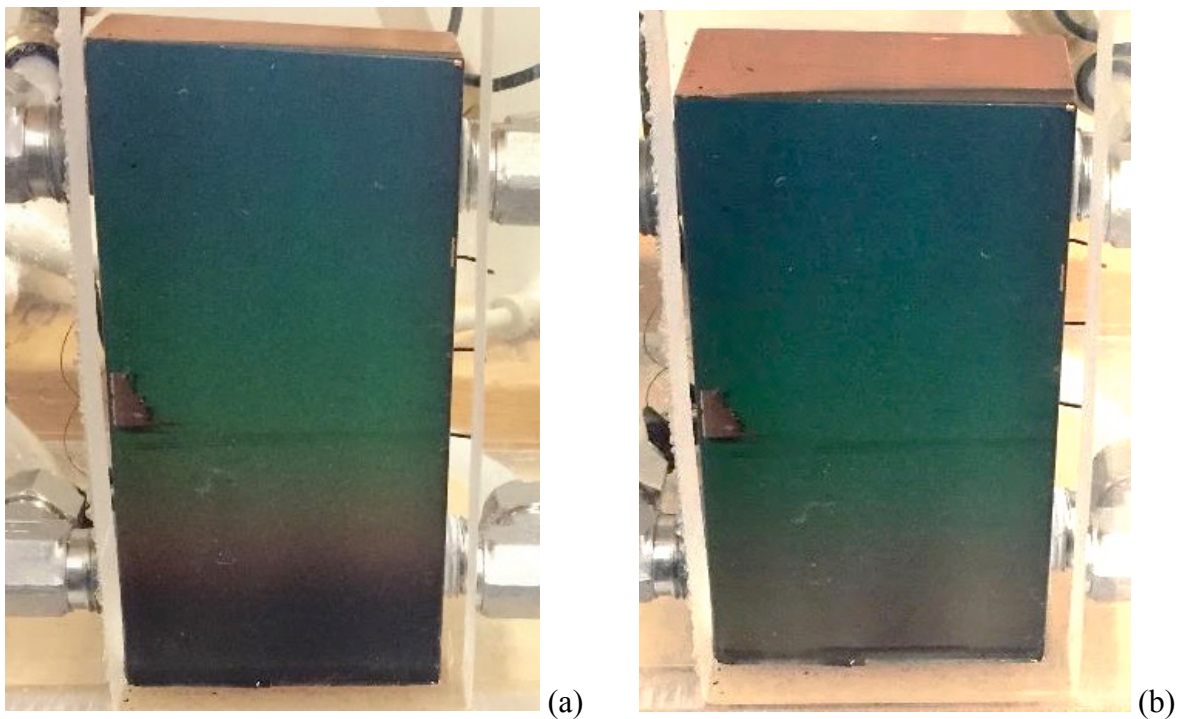


Figure 10: Pictures taken from iPhone 6 (a) Trial I (b) Trial II

Once steady state was reached, the RTD values at three locations were recorded. A suitable sample area was chosen from the picture. Variation of Hue along plate length was obtained using the MATLAB code for both trials. A suitable polynomial fit is used to obtain a relation between Plate length (pixels) and Hue across the selected region. The three markers protruding from the right side of the plate in Fig. 10 are used to identify the vertical location of

the RTDs. The three temperature readings are plotted against the Y-coordinates of the 2-D pixel map. A correction factor of $4.6\ \Omega$ is subtracted as line resistance. A linear relationship is obtained between temperature and plate length (pixels). Using the two relations mentioned above, a calibration curve is obtained for both trials and compared.

Chapter 3: Results

The RGB and Hue data plotted against plate length is shown in Figures 11(a) and 11(b) expressed as RGB and HSL values, respectively. Fig. 12 shows the Hue plot with a fourth degree polynomial fit. The resulting calibration curve for Trial I is shown in Fig. 13. A seventh degree polynomial well defines the Hue-Temperature relationship.

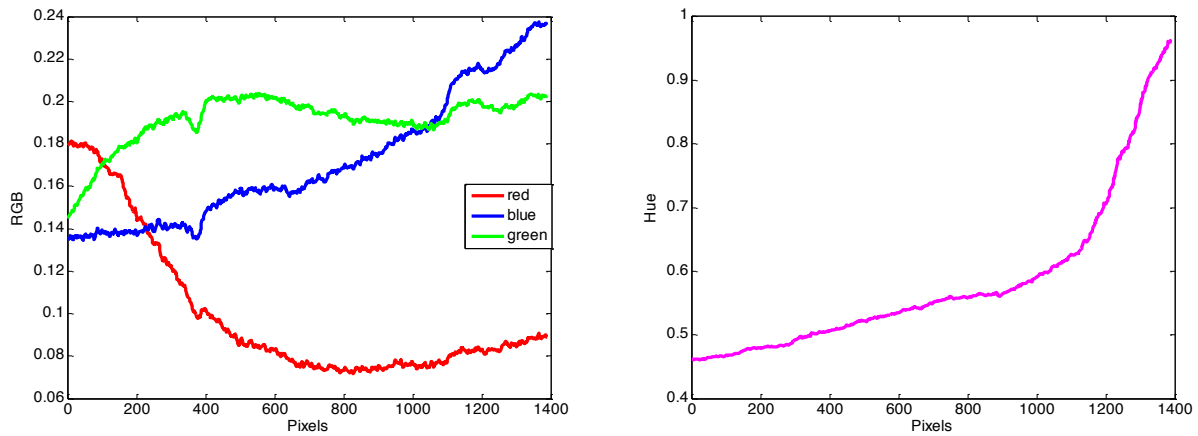


Figure 11: Trial I (a) RGB data (b) Hue Data

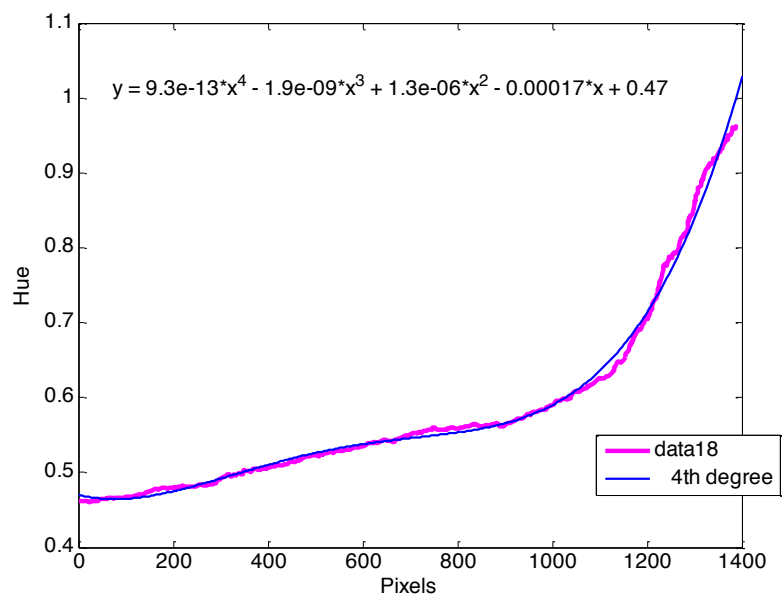


Figure 12: Trial I Hue data with 4th degree polynomial fit

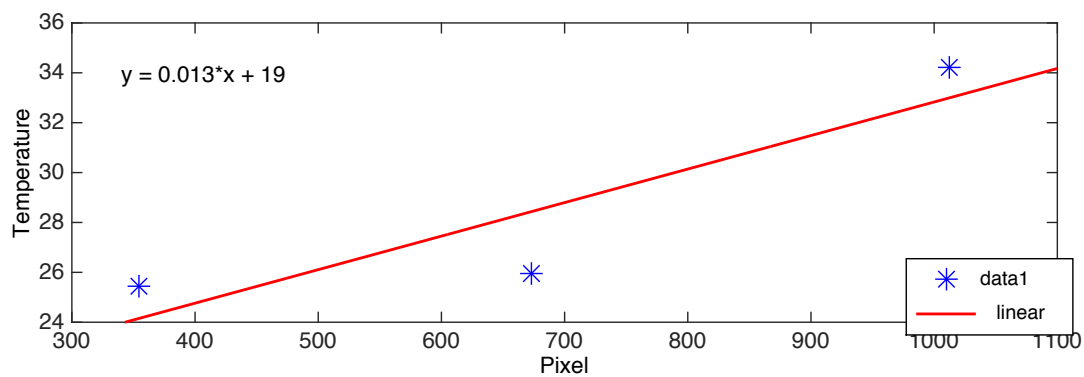


Figure 13: Trial I Temperature data with linear fit

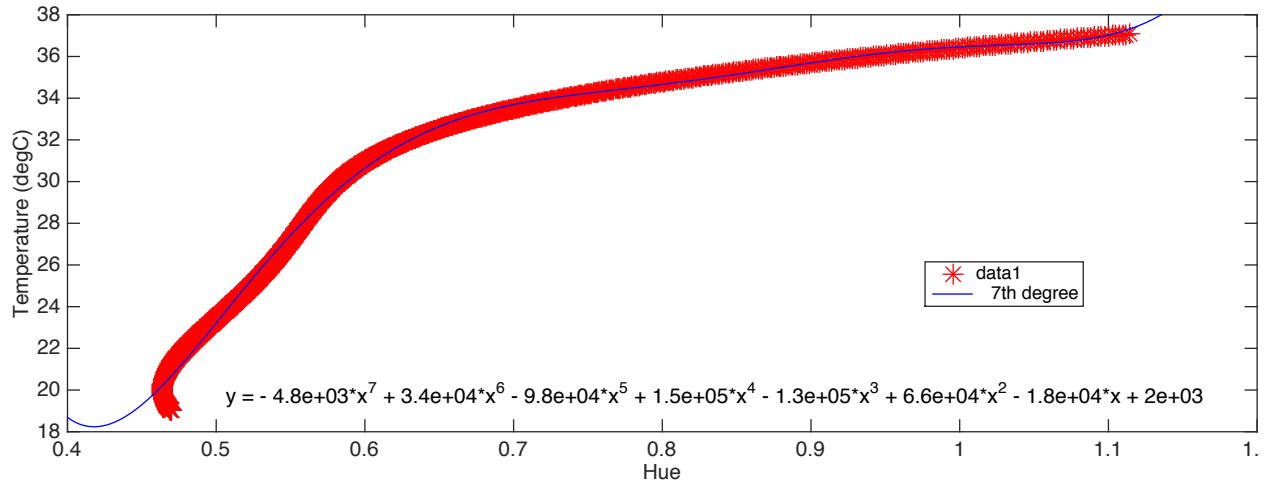


Figure 14: Trial I Calibration Curve

The results of Trial II are shown in this section in the same manner. The RGB and Hue data plotted against plate length is shown in Figures 16(a) and 16(b). Fig. 17 shows the Hue plot with a fourth degree polynomial fit. The calibration curve for Trial II is shown in Fig. 18. A seventh degree polynomial well defines the Hue-Temperature relationship.

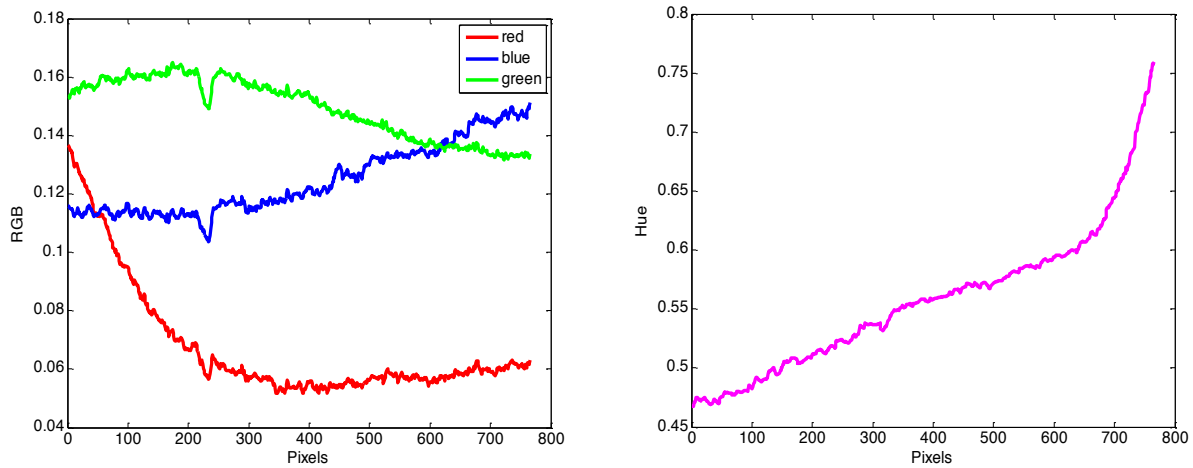


Figure 15: Trial II (a) RGB data (b) Hue Data

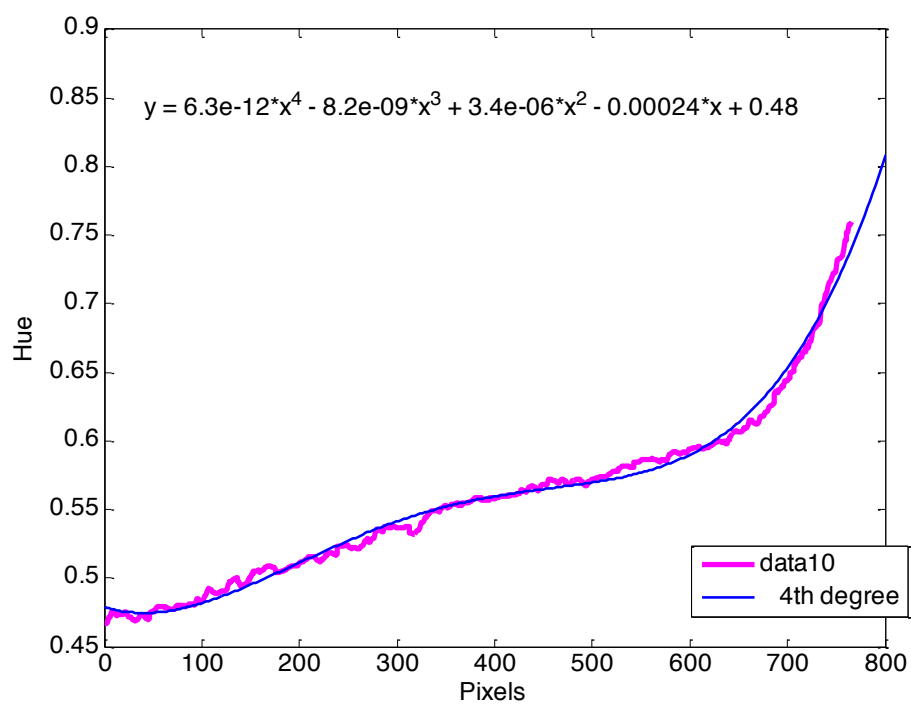


Figure 16: Trial II Hue data with 4th degree polynomial fit

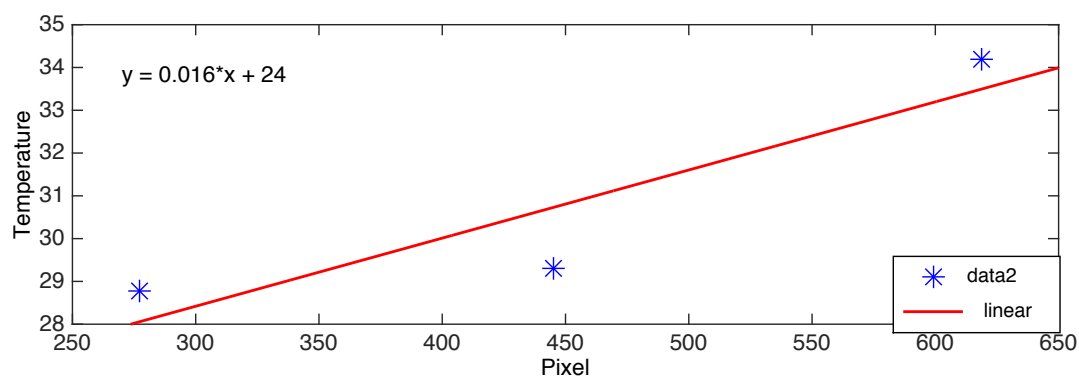


Figure 17: Trial II Temperature data with linear fit

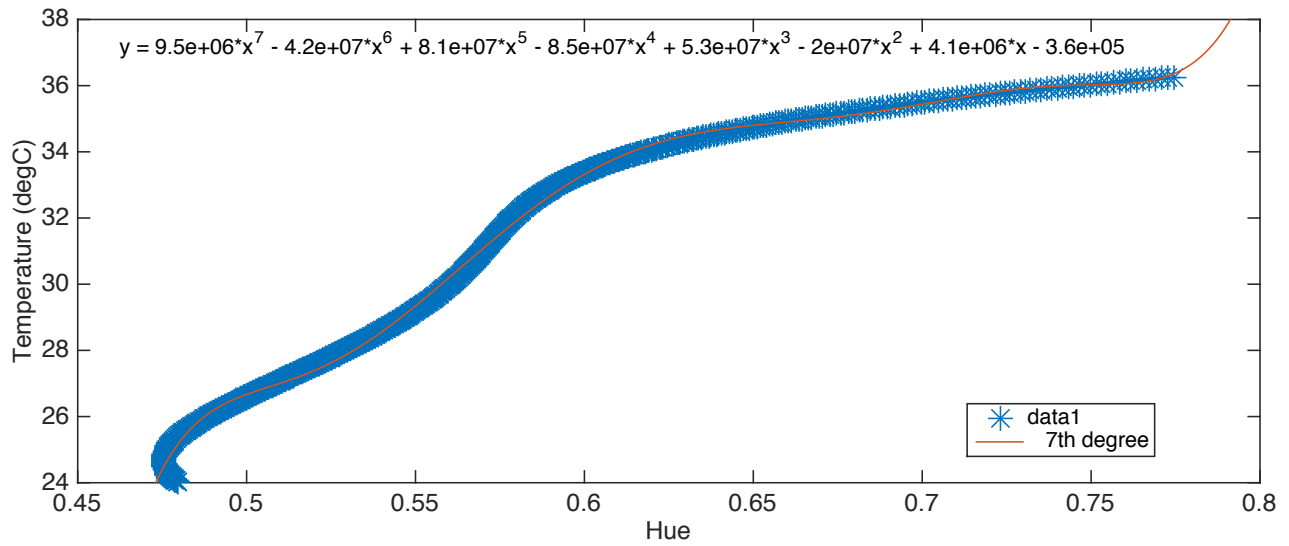


Figure 18: Trial II Calibration Curve

Fig. 19 compares the calibration curves in a single plot. The curves show consistency in shape; however, they show a shift in temperature range readings. This indicates there are several issues with the calibration that must be examined in more detail.

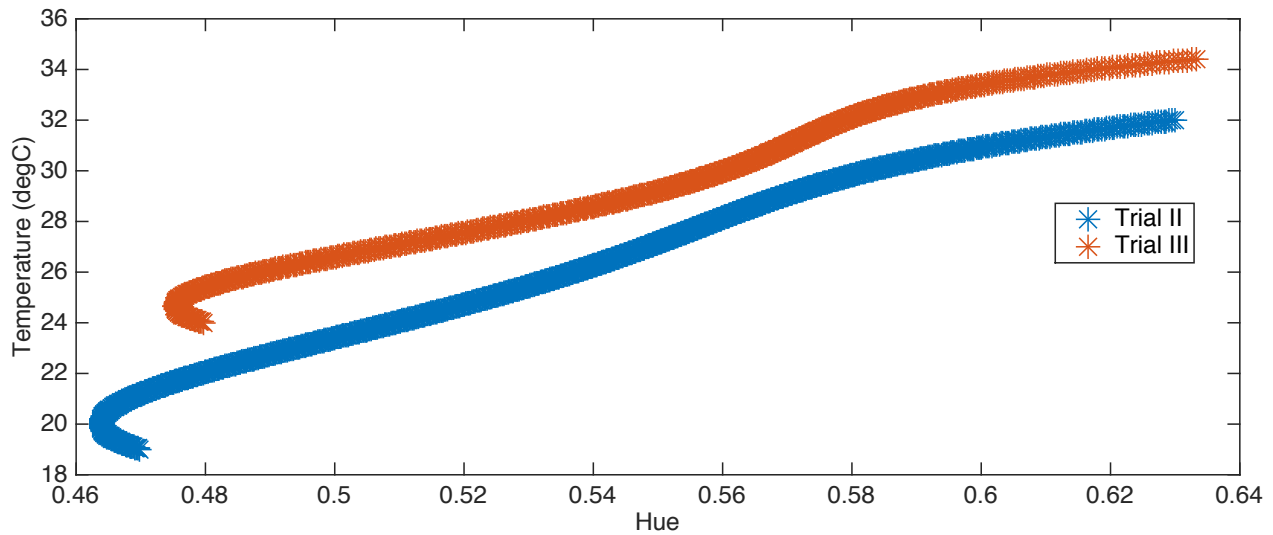


Figure 19: Calibration Curves for both trials

Firstly, the temperature data from the RTDs, as illustrated in Figures 13 and 17, did not yield a perfectly linear pattern. The wires connected to the RTDs had a very high line resistance and moreover, the banana clips used to read data from the multi-meter had poor electrical contact to the RTD leads, resulting in variations in the measured resistance that did not correspond to actual temperature changes. Thorough inspection of the RTD readings is recommended.

Secondly, the temperature range obtained in the calibration curves go beyond the range set on the water chillers. The actual temperature of the fluid entering the copper plate must be checked to validate the readings. Lastly, the plate coated with TLCs must be handled with caution to avoid scratches and damages on the test surface. There is scope for efficiency and design improvements that require recalibration of the RTDs, improve the experimental setup, and improve the insulation of the copper block.

Chapter 4: Summary

4.1 Conclusion

The calibration curves obtained through these experiments clearly show that hue increases with increases in temperature and their relationship is defined using a seventh degree polynomial. The calibration curve differs according to various temperature ranges and ambient illumination. Liquid crystals have proven to be a useful tool for full-coverage temperature measurement and are ideal for quick, transient heat transfer measurements. It has been successful at yielding repeatable measurements and in maintaining a unique curve trend. Calibration of the liquid crystals each time before use improves the accuracy of data. This can be achieved within a short time frame by using the designed calibration unit. The copper block is replaceable and hence several batches of liquid crystals can be calibrated with ease. Furthermore, there is room for installment of more number of RTDs to improve data accuracy. The working of the calibration unit is evident and therefore it is ready for future development.

4.2 Future Work

There is great scope for improvement in the design of the calibration unit and the data acquisition methodology. The functioning of the RTDs can be crosschecked either by swapping the RTDs around or confirming using a standard resistance. Wires with high line resistance can be replaced with low resistance ones. The banana clips offer bad contact surface to the wires. Soldering the wires can be helpful to secure them in order to obtain steady readings. As mentioned previously, the temperature data is sensitive to ambient light. Different lighting conditions can be simulated to obtain the desired light input during calibration; specifically, one that imitates the on-site lighting. Reflections on the photographs should be avoided and can be achieved using

polarized sheets. The temperatures of the fluid chillers can be checked for accuracy to avoid false data. This research can serve as a baseline to conduct transient heat transfer experiments using TLCs and validate results using known data. Furthermore, heat transfer coefficients can be evaluated using the temperature response time and fluid reference temperature distributions.

Appendix A: MATLAB Code

```
clc
clear all

image=imread('color1.JPG');
R1=double(image(311:1700,1109:1553,1));
G1=double(image(311:1700,1109:1553,2));
B1=double(image(311:1700,1109:1553,3));
%*****
image=imread('color2.JPG');

R2=double(image(835:1600,1061:1288,1));
G2=double(image(835:1600,1061:1288,2));
B2=double(image(835:1600,1061:1288,3));

r1=mean(R1');
g1=mean(G1');
b1=mean(B1');

r2=mean(R2');
g2=mean(G2');
b2=mean(B2');

%*****RGB*****
red1=r1'/255
green1=g1'/255
blue1=b1'/255
figure(1)
len1 = length(red1):-1:1;
plot(len1,red1,'r',len1,blue1,'b',len1,green1,'g','linewidth',3)
xlabel('Pixels','FontSize',14)
ylabel('RGB','FontSize',14)

red2=r2'/255
green2=g2'/255
blue2=b2'/255
figure(2)
len2 = length(red2):-1:1;
plot(len2,red2,'r',len2,blue2,'b',len2,green2,'g','linewidth',3)
xlabel('Pixels','FontSize',14)
ylabel('RGB','FontSize',14)
legend('red','blue','green')
%*****Hue*****

[h1 s1 s1] = rgb2hsl1(red1,blue1,green1);
figure(3)
Len1 = 1:length(h1);
plot(Len1,h1,'m','linewidth',3)
xlabel('Pixels','FontSize',14)
```

```

ylabel('Hue','FontSize',14)
legend('red','blue','green')

[h2 s2 l2] = rgb2hsl1(red2,blue2,green2);
figure(4)
Len2 = 1:length(h2);
plot(Len2,h2,'m','linewidth',3)
xlabel('Pixels','FontSize',14)
ylabel('Hue','FontSize',14)

%*****Data for Trial 1*****
H1 = [h1(1700-1347+1), h1(1700-1028+1), h1(1700-689+1)]
L1 = [len1(1700-1347+1), len1(1700-1028+1), len1(1700-689+1)]
T1 = [25.43 25.94 34.2];
x1= 1:length(h1)
Hue1 = 9.3e-13*x1.^4 - 1.9e-9*x1.^3 + 1.3e-6*x1.^2 - 0.00017*x1 + 0.47

figure(5)
plot(L1,T1,'*','MarkerSize',13)
xlabel('Pixel','FontSize',14)
ylabel('Temperature','FontSize',14)

Temp1 = 0.013*x1+19

figure(6)
plot(Hue1,Temp1,'*','color','r','MarkerSize',13)
ylabel('Temperature (degC)','FontSize',14)
xlabel('Hue','FontSize',14)

%*****Data for Trial 2*****
H2 = [h2(1600-1324+1), h2(1600-1156+1), h2(1600-982+1)];
L2 = [len1(1600-1324+1), len1(1600-1156+1), len1(1600-982+1)];
T2 = [28.78 29.3 34.2];

x2= 1:length(h2)
Hue2 = 6.3e-12*x2.^4 - 8.2e-9*x2.^3 + 3.4e-6*x2.^2 - 0.00024*x2+0.48;

figure(7)
plot(L2,T2,'*','MarkerSize',13)
xlabel('Pixel','FontSize',14)
ylabel('Temperature','FontSize',14)

% Temp2 = 7.3e-5*x2.^2 - 0.05*x2 + 37;
Temp2 = 0.016*x2+24
figure(8)
%
% plot(Hue1,Temp1,'*','MarkerSize',13)
% ylabel('Temperature (degC)','FontSize',14)
% xlabel('Hue','FontSize',14)
% hold on
plot(Hue2,Temp2,'*','MarkerSize',13)
ylabel('Temperature (degC)','FontSize',14)
xlabel('Hue','FontSize',14)
% hold off

```

```
legend('Trial II','Trial III')
```

Note: The following function has been referenced from www.mathworks.com

```
function [h s l] = rgb2hsl(R,G,B)
```

```
r = R/255;
g = G/255;
b = B/255;
[m n]=size(r);
H=zeros(m,n);
```

```
for i=1:m
```

```
    for j=1:n
```

```
        [Cmax,index] = max([r(i,j) g(i,j) b(i,j)]);
        Cmin = min([r(i,j) g(i,j) b(i,j)]);
        delta = Cmax-Cmin;
```

```
        L(i,j) = (Cmax+Cmin)/2;
```

```
        if(L(i,j)<0.5)
            S(i,j)=delta/(Cmax+Cmin);
        else
            S(i,j)=delta/(2-Cmax-Cmin);
        end
```

```
% H = cos-1[ (R - ΩG - ΩB)/?R≤ + G≤ + B≤ - RG - RB - GB ]
```

```
H(i,j) = atand(sqrt(3)*(g(i,j)-b(i,j))/(2*r(i,j)-g(i,j)-b(i,j)));
% if b(i,j)>g(i,j)
    if H(i,j)<0
        H(i,j)=360+H(i,j);
    end
```

```
if S(i,j)==0
```

```
    H(i,j)=0;
end
```

```
if H(i,j)>360
    H(i,j)=H(i,j)-360;
end
```

```
end
```

```
end
```

```
h=H;  
s=S*100;  
l=L*100;
```

```
end
```

Appendix B: Finite Element Analysis Results

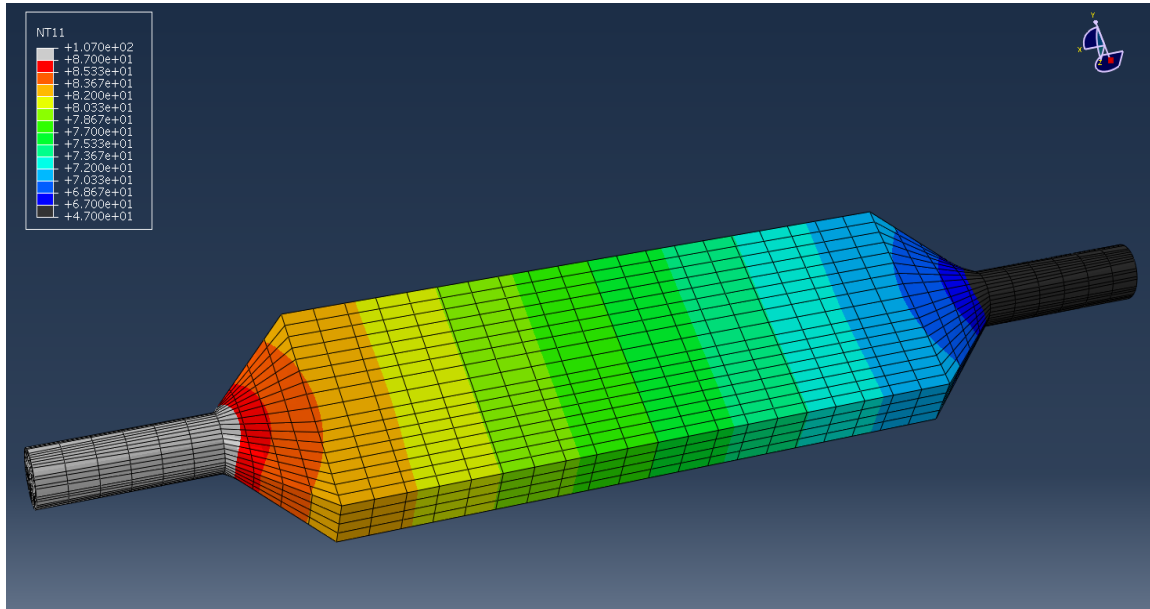


Figure B 1: Finite Element Analysis on Initial Plate Design

Simulation Settings: 3-D Deformable; Heat Transfer between 47 °F and 107 °F; Mesh Size 0.9.

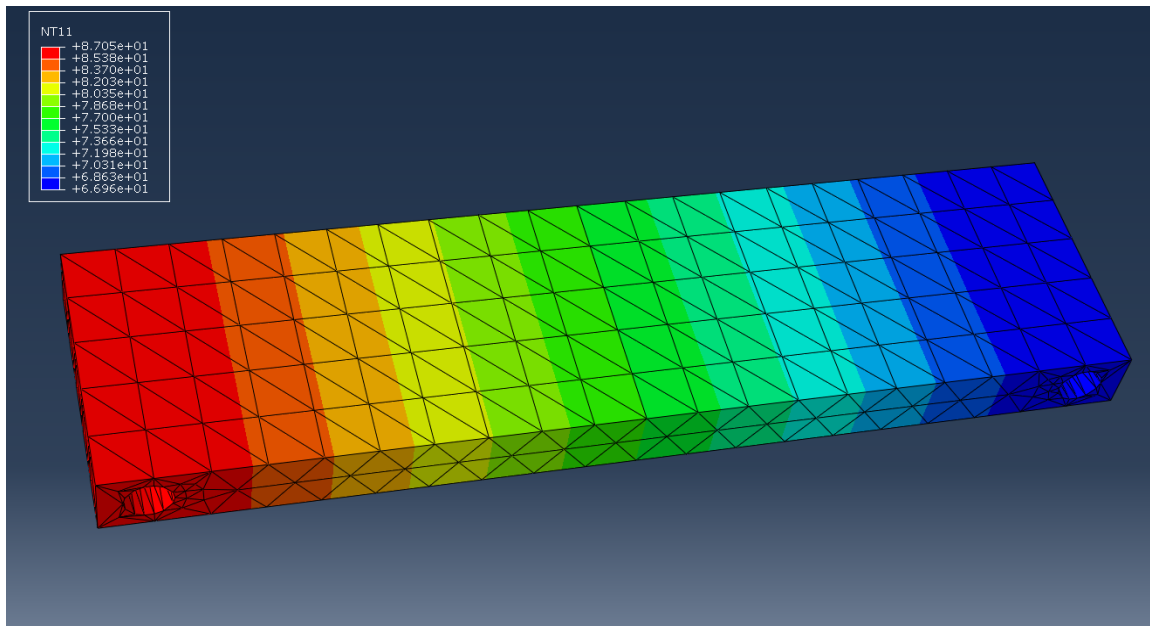


Figure B 2: Finite Element Analysis on Final Plate Design

Simulation Settings: 3-D Deformable; Heat Transfer between 67 °F and 87 °F; Mesh Size 1.

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